

# Supersymmetry with a Sister Higgs

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work w/ P. Fox and N. Weiner

arXiv:1207.5522, 1207.5499

SILAF AE 2012  
ICTP-SAIFR, Sao Paulo

# Motivation

$$m_{h^0} \simeq 125 \text{ GeV}$$

&

SUSY

# Motivation

$$m_{h^0} \simeq 125 \text{ GeV}$$

In **MSSM**, this mass is weird.

Higgs quartic is set by EW D-terms:

$$V_{\text{quartic}} = \frac{g^2 + g'^2}{8} (|H_u|^2 - |H_d|^2)^2$$

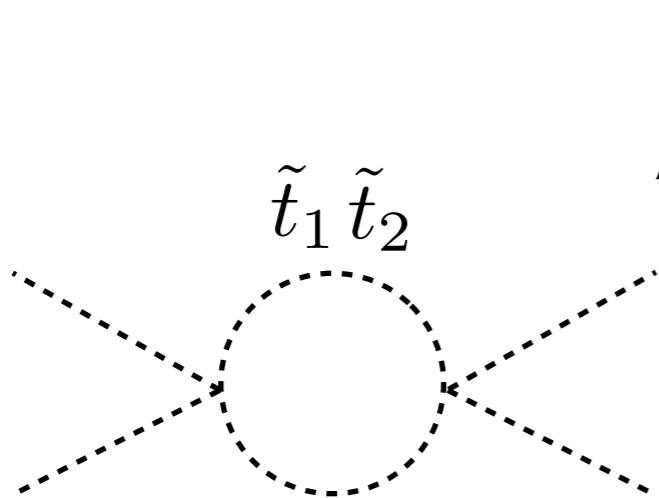
This sets a natural range for  $m_{h^0}$ :

$$m_{h^0} < m_{Z^0} \quad (\text{tree level})$$

# Motivation

$$m_{h^0} \simeq 125 \text{ GeV}$$

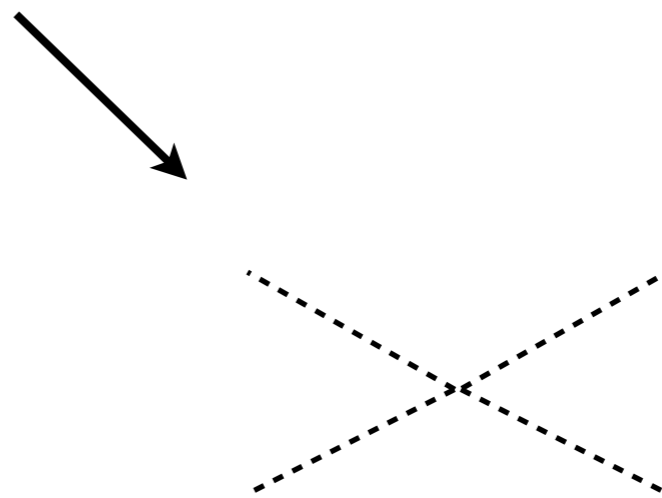
The Higgs quartic is larger than the D-terms told us  
(LEP told us that already, but not by how much)



large loop corrections



fine-tuning of  $\sim 10^3$



extra tree-level



SSM has more structure

# Motivation

**NMSSM** is a simple way to generate extra quartic by coupling the higgs sector to a new complete singlet

$$W \supset \lambda \phi H_u H_d$$

$$V_{\text{quartic}} = \frac{g^2 + g'^2}{8} (|H_u|^2 - |H_d|^2)^2 + \lambda^2 |H_u H_d|^2$$

$$\Rightarrow m_{h^0}^2 = m_{Z^0}^2 \cos^2 2\beta + \lambda^2 v_{\text{ew}}^2 \sin^2 2\beta$$

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***Tension:***

$\lambda$  runs small at low energies

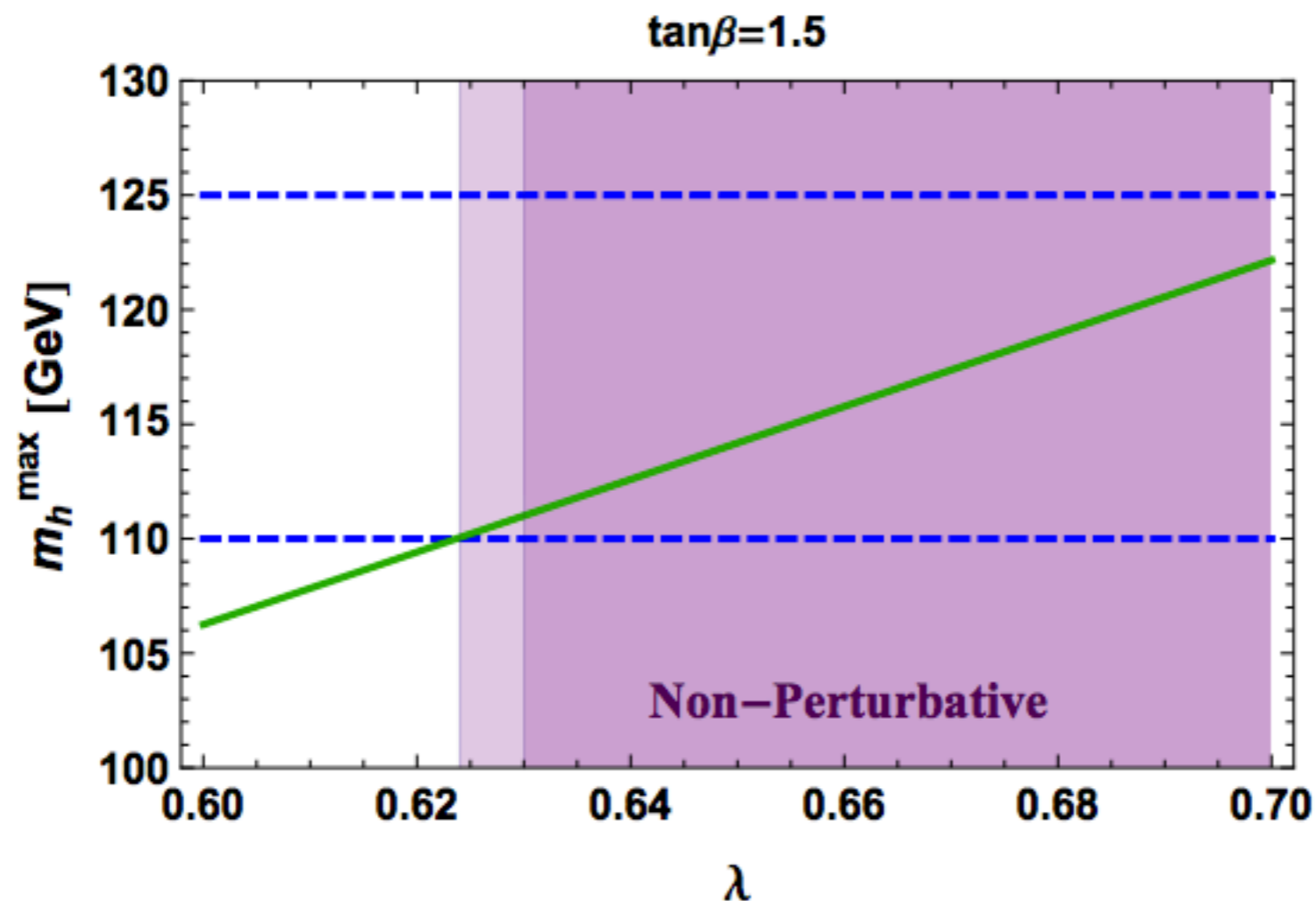
$m_{h^0} \simeq 125$  GeV pushes  $\lambda$  to its perturbativity edge

# Motivation

$$\beta_\lambda = \lambda \left( 5\lambda^2 + 3y_t^2 - 3g^2 - \frac{3}{5}g'^2 \right)$$

top yukawa drives  $\lambda$   
non-perturbative

gauge couplings  
counteract top yukawa



Agashe, Cui, Franceschini  
arXiv:1209.2115

# Motivation

$$\beta_\lambda = \lambda \left( 5\lambda^2 + 3y_t^2 - 3g^2 - \frac{3}{5}g'^2 - \#g_s^2 \right)$$

problem suggests its own remedy:

add **new gauge interactions** to slow running of  $\lambda$

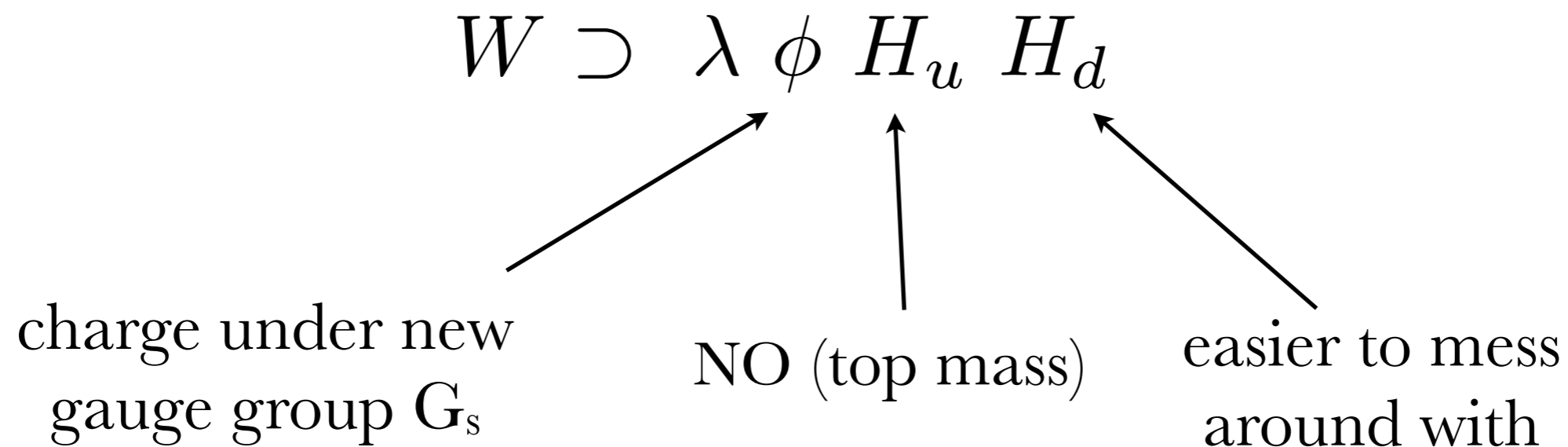


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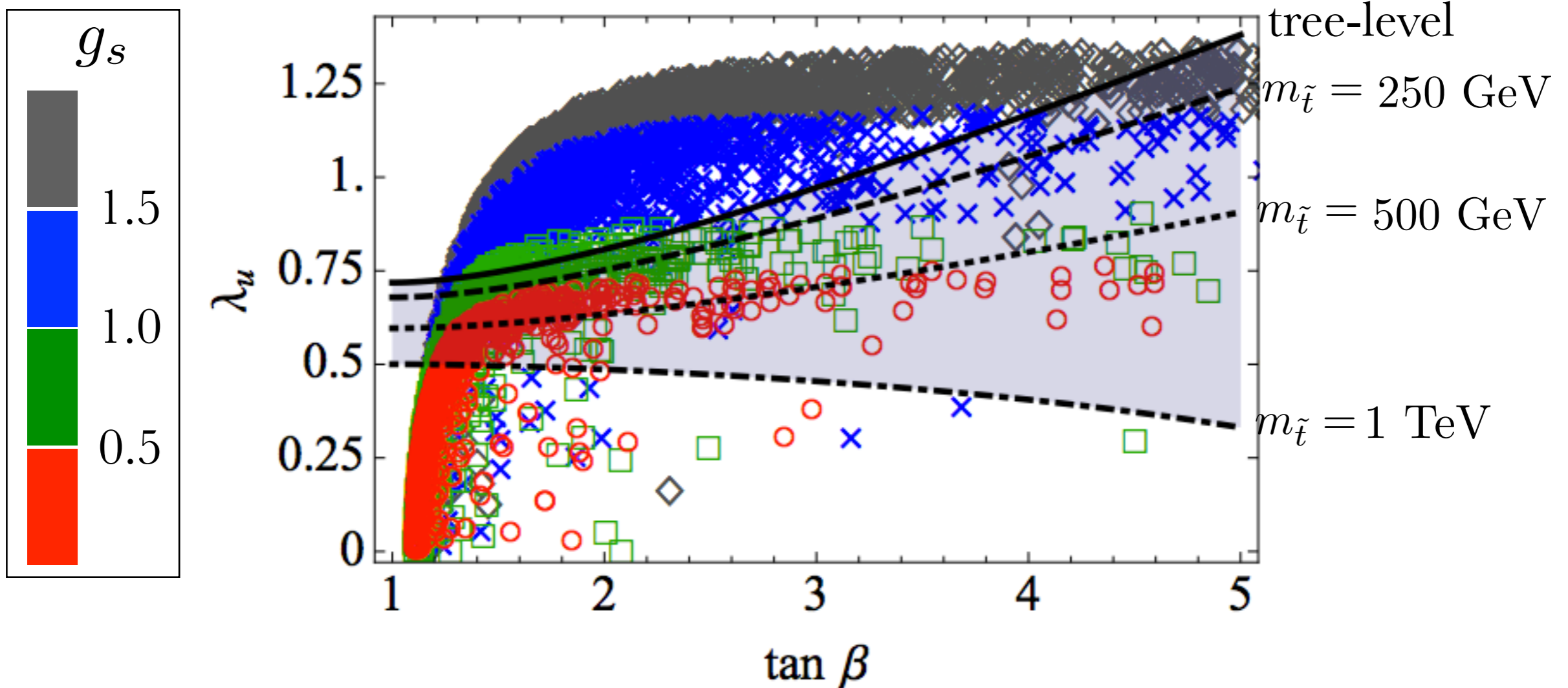
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# Motivation

Example  $G_s = \text{SU}(2)$ ,  $\beta_{g_s} = 0$  at 1-loop:

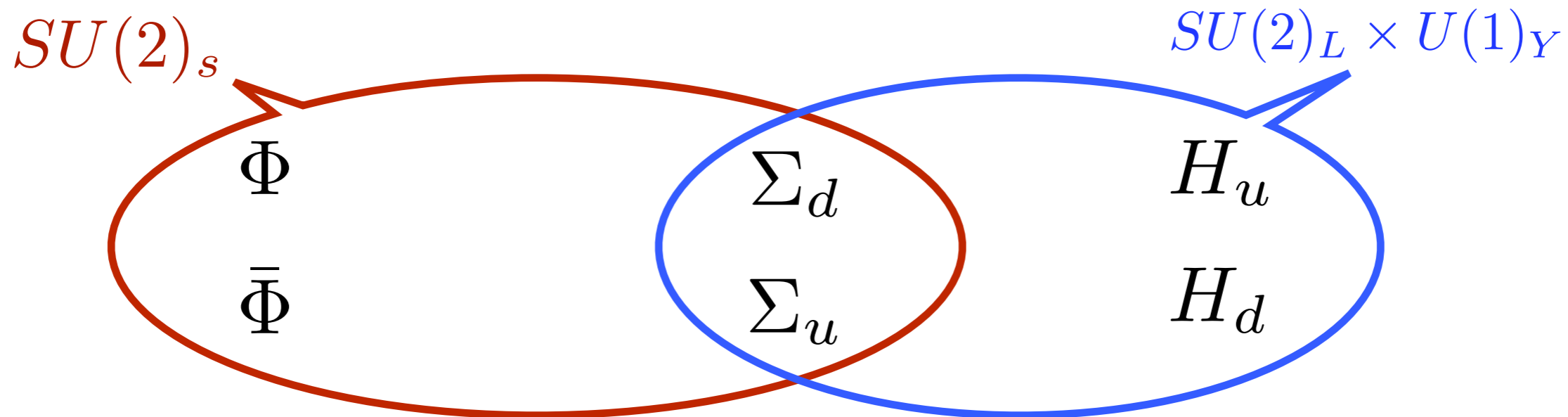
$$\beta_\lambda = \lambda \left( 5\lambda^2 + 3y_t^2 - 3g^2 - \frac{3}{5}g'^2 - 3g_s^2 \right)$$



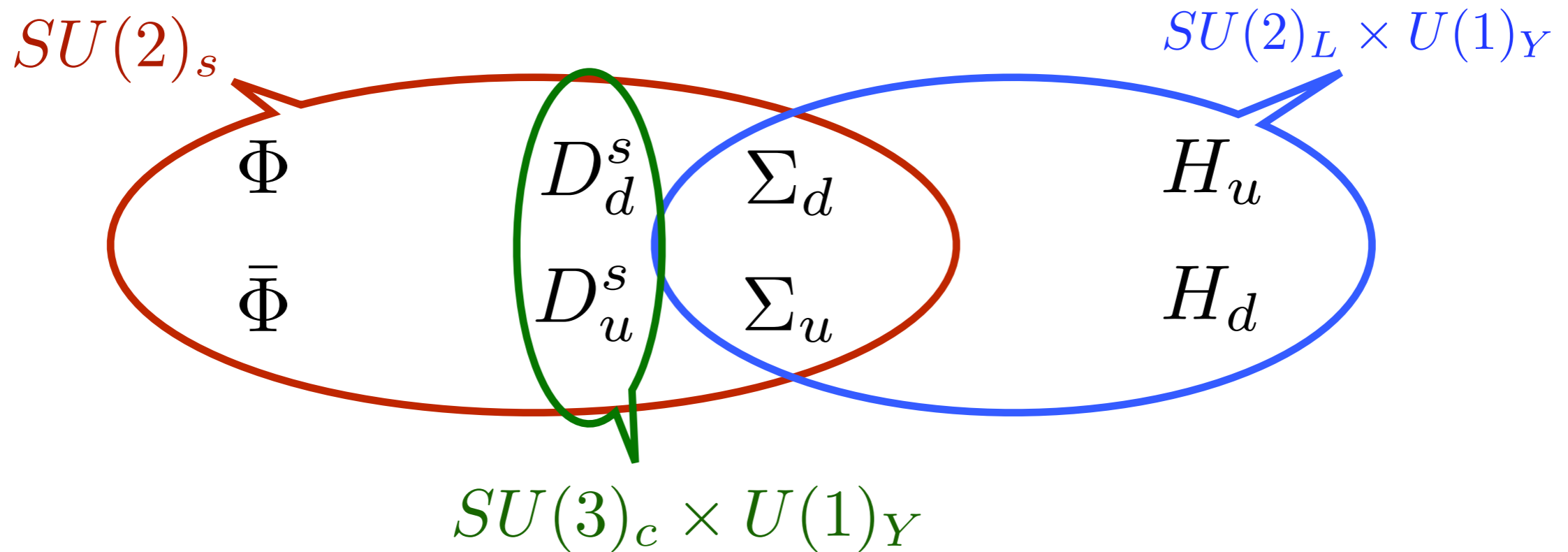
# Outline

- ➔ Concrete example of Sister Higgs
- ➔ Simplified low energy limit
  - ➔ type-I 2HDM + Inert doublet
  - ➔ modifications of higgs production and decay
- ➔ New RPV operator
- ➔ Sister-quarks, modified squark and gluino decays
- ➔  $Z'$ , new dark matter forces

# Sister Higgs



# Sister Higgs

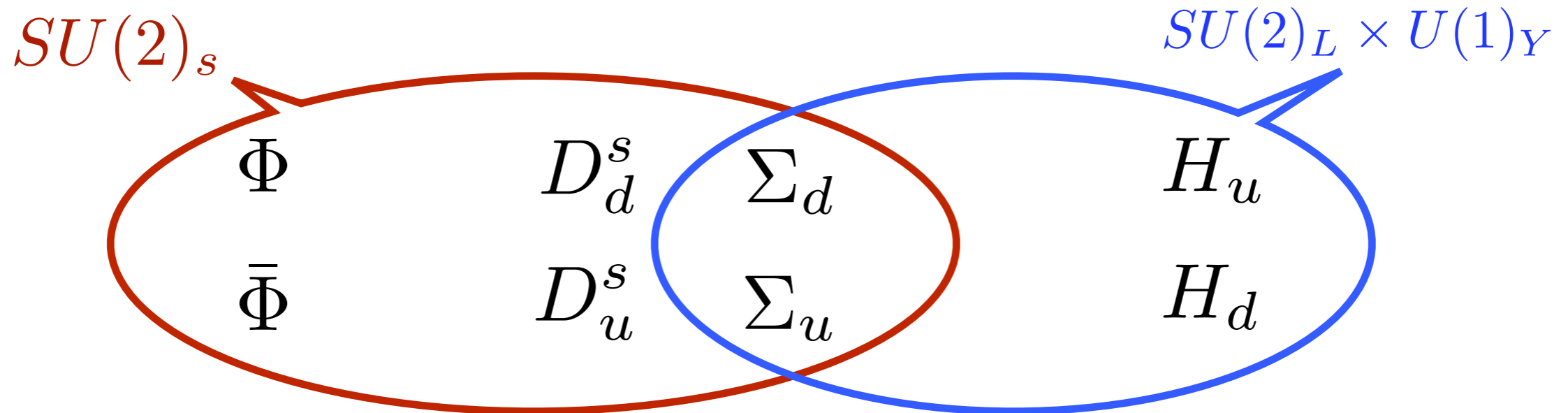


Sister-quarks  $D^s$ :

complete  $\Sigma_{u,d}$   $SU(5)$  multiplet (unification)

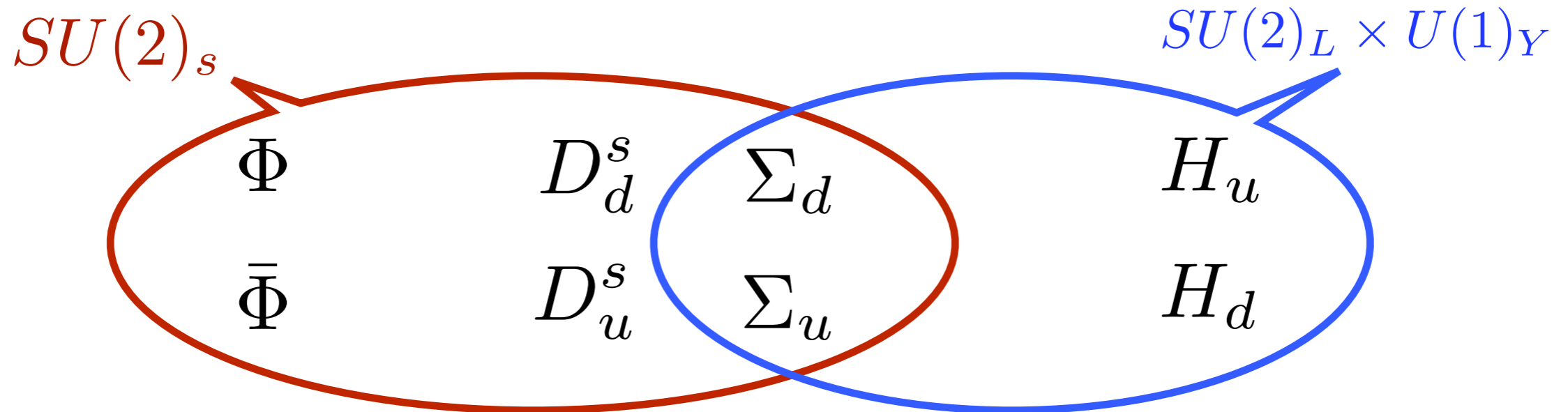
$\beta_{g_s} = 0$  at 1-loop (running of  $\lambda$ )

# Sister Higgs



$$W = \mu_\phi \Phi \bar{\Phi} + \mu_\Sigma \Sigma_u \Sigma_d + \mu_H H_u H_d + \mu_D D_u^s D_d^s \quad \mu \text{ terms}$$

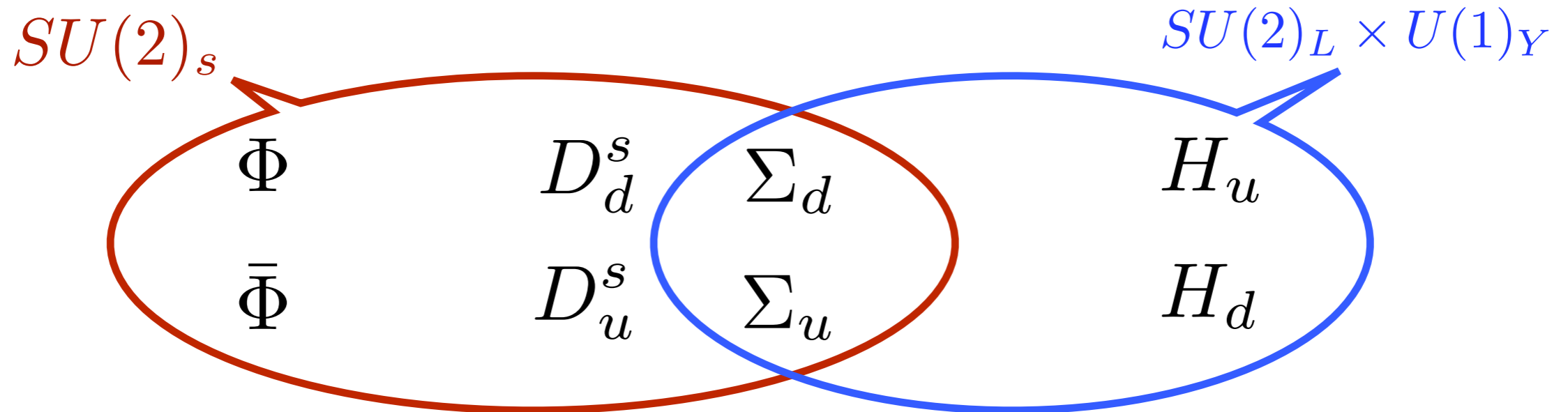
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$$+ \lambda_u \Phi H_u \Sigma_d + \lambda_d \bar{\Phi} H_d \Sigma_u \quad \text{NMSSM-type terms}$$

# Sister Higgs



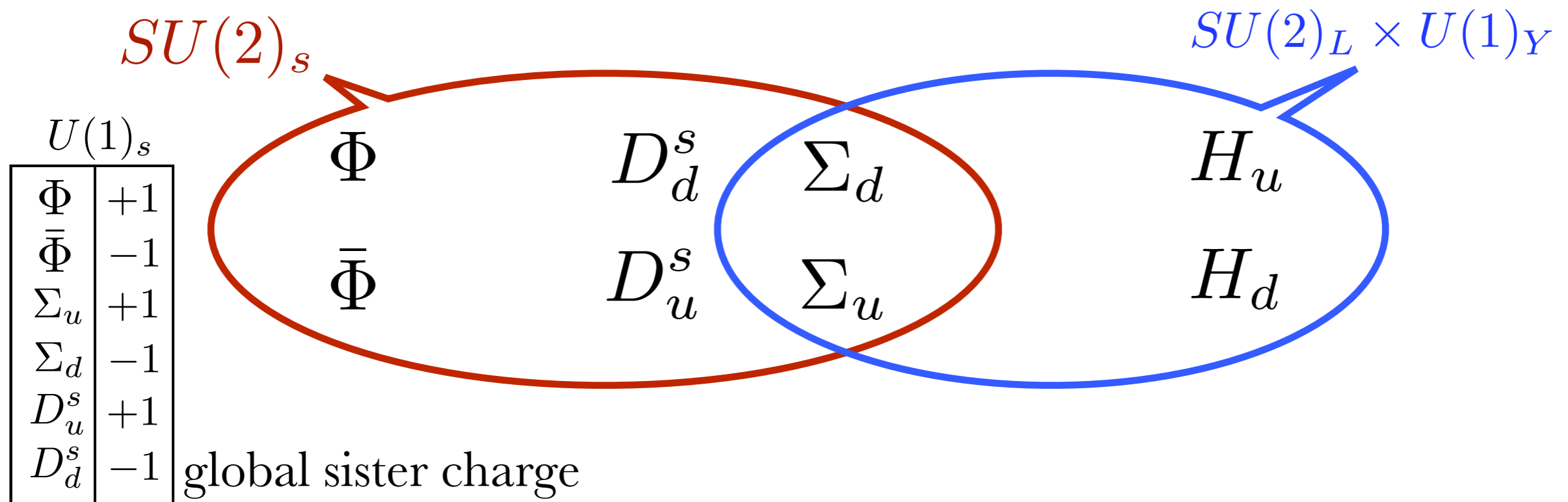
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$$+ y_u Q H_u U^c + y_d Q H_d D^c + y_\ell L H_d E^c \quad \text{yukawas}$$



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# Outline

→ Sister Higgs

→ Simplified low energy limit

→ type-I 2HDM + Inert doublet

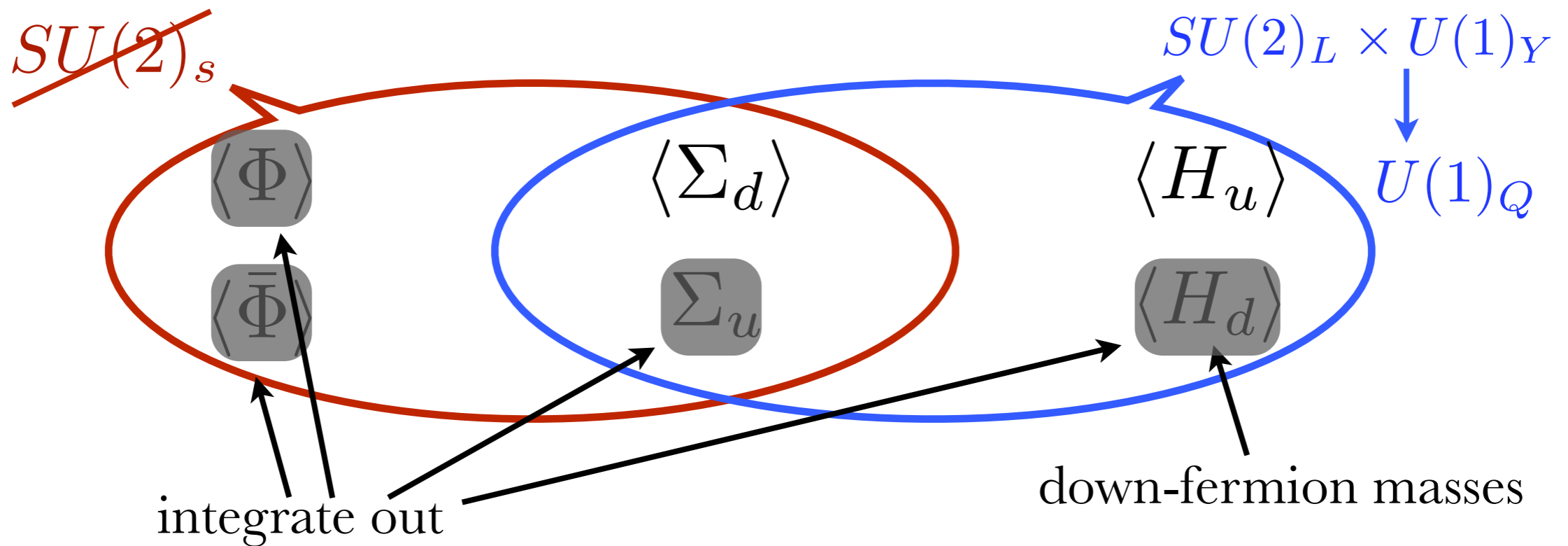
→ modifications of higgs production and decay

→ New RPV operators

→ Sister-quarks, modified squark and gluino decays

→  $Z'$ , new dark matter forces

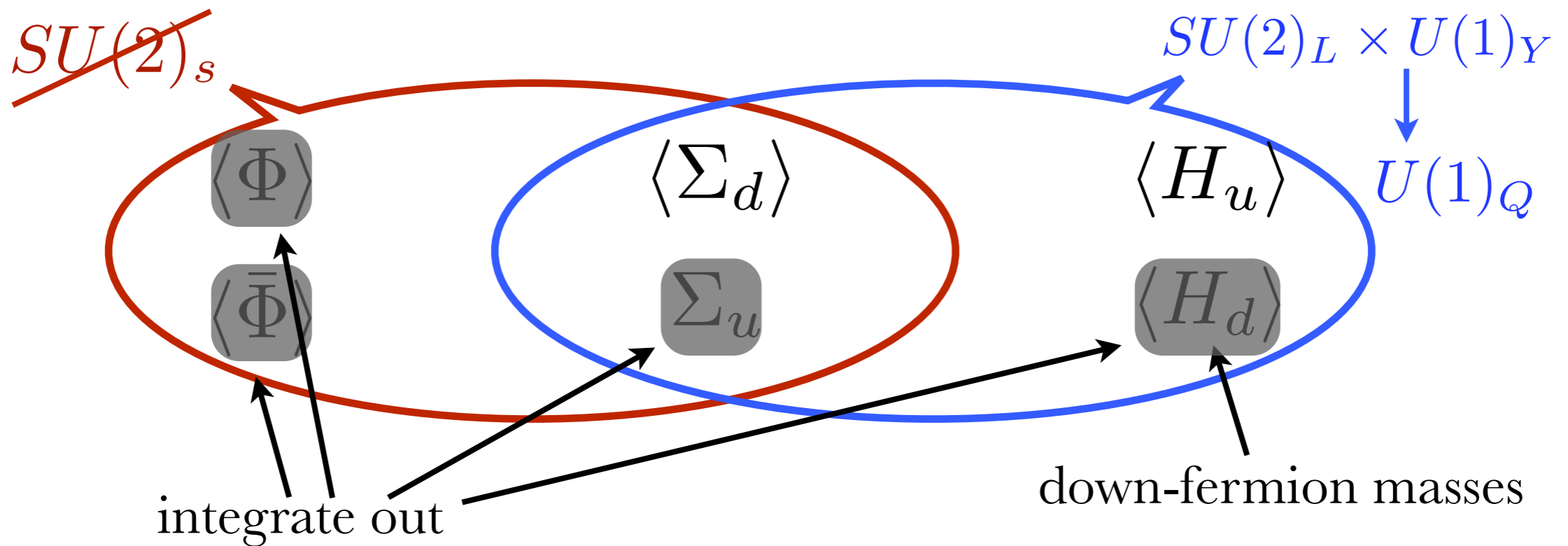
# Low Energy Higgs Sector



$$\begin{aligned}
 W = & \mu_\phi \Phi \bar{\Phi} + \mu_\Sigma \Sigma_u \Sigma_d + \mu_H H_u H_d && \mu \text{ terms} \\
 & + \lambda_u \Phi H_u \Sigma_d + \lambda_d \bar{\Phi} H_d \Sigma_u && \text{NMSSM-type terms} \\
 & + y_u Q H_u U^c + y_d Q H_d D^c + y_\ell L H_d E^c && \text{yukawas}
 \end{aligned}$$

*small*

# Low Energy Higgs Sector



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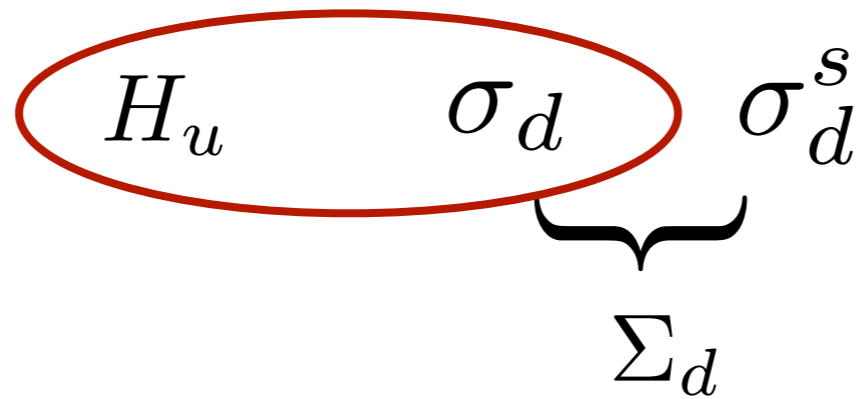
~~small~~

$$+ y_u Q H_u U^c + y_d \frac{B\mu}{m_{H_d}^2} Q H_u^* D^c + y_\ell \frac{B\mu}{m_{H_d}^2} L H_u^* E^c$$

# Low Energy Higgs Sector

$$H_u \quad \underbrace{\sigma_d \quad \sigma_d^s}_{\Sigma_d}$$

# Low Energy Higgs Sector



2 Higgs Doublet Model

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2 Higgs Doublet Model

+

Inert Doublet

# Low Energy Higgs Sector

$$H_u \quad \underbrace{\sigma_d \quad \sigma_d^s}_{\Sigma_d}$$

$$W \supset y_u Q H_u U^c + y'_d Q H_u^* D^c + y'_\ell L H_u^* E^c$$

**Type-I** 2 Higgs Doublet Model

+

Inert Doublet



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# Higgs production and decays

$$\tan\beta \equiv \frac{\langle H_u^0 \rangle}{\langle \sigma_d^0 \rangle} \quad \begin{pmatrix} h^0 \\ H^0 \end{pmatrix} = R(\alpha) \begin{pmatrix} H_u^0 \\ \sigma_d^0 \end{pmatrix}$$

$$h^0 VV : m_V \sin(\beta - \alpha)$$

$$h^0 \bar{f} f : \frac{m_f}{v_{\text{ew}}} \frac{\cos\alpha}{\sin\beta}$$

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For simplified limit of Sister Higgs (not generic type-I feature):

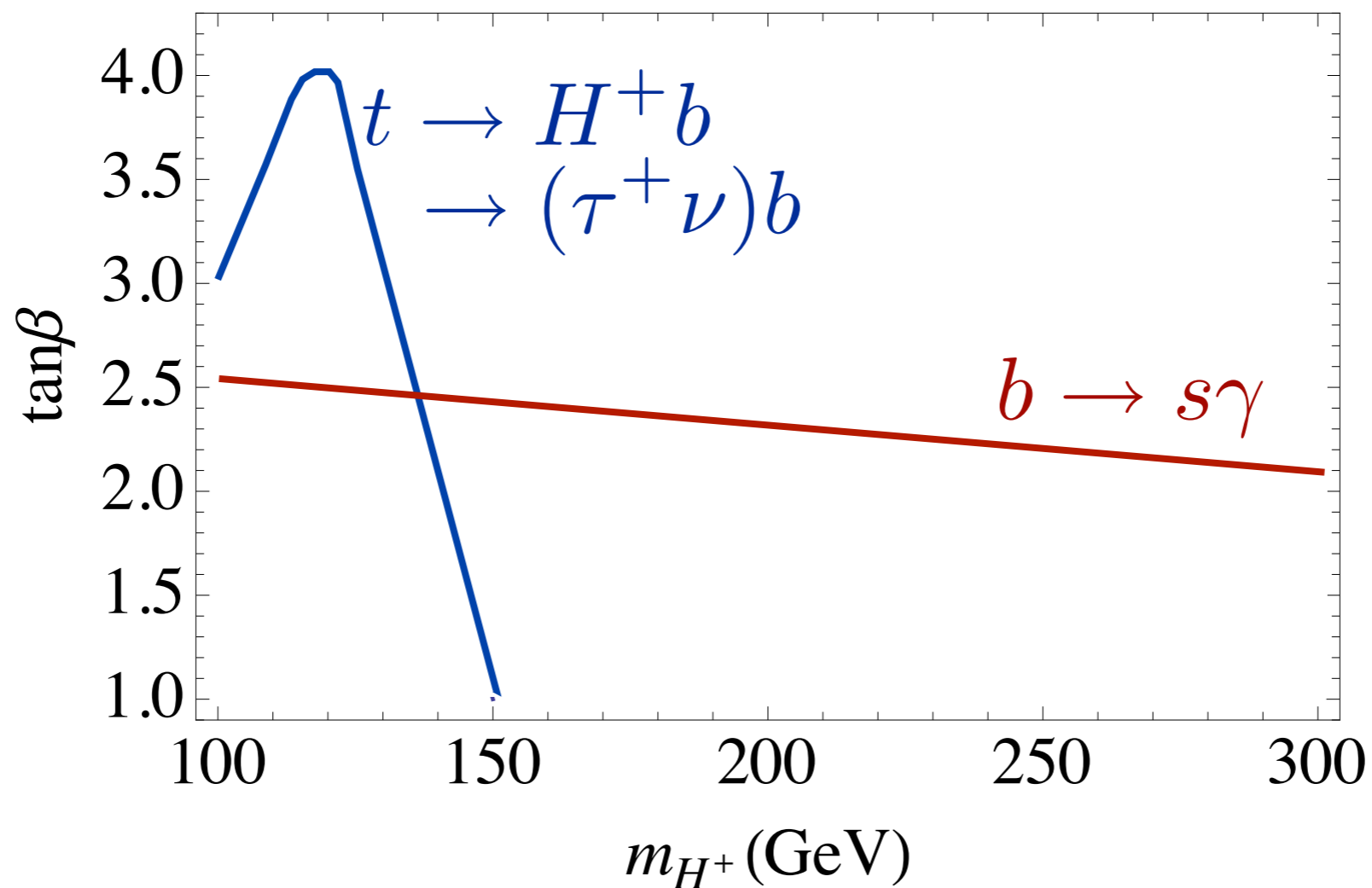
$$gg \rightarrow h^0 \rightarrow f \bar{f} \quad \text{enhanced}$$

$$h^0 \rightarrow VV \quad \text{suppressed}$$

# Higgs production and decays

$h^0 \rightarrow \gamma\gamma$  suppression is compensated by  $H^\pm, \sigma_s^\pm$  loops

for light  $H^\pm, \sigma_s^\pm$  and small  $\tan\beta$



# Higgs production and decays

$$H^{\pm} \rightarrow W b \bar{b}, cs, \tau \nu$$

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Electroweak precision constrains  $H^{\pm}, H^0, A^0$  splittings

$$\text{light } H^{\pm} \Rightarrow \text{light } H^0, A^0$$

$$\text{suppressed } H^0 \bar{b} b : \frac{m_b}{v_{\text{ew}}} \frac{\sin \alpha}{\sin \beta} \qquad \text{Type-II} : \frac{m_b}{v_{\text{ew}}} \frac{\cos \alpha}{\cos \beta}$$

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$$H^0 \rightarrow WW, ZZ$$



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# New RPV operator

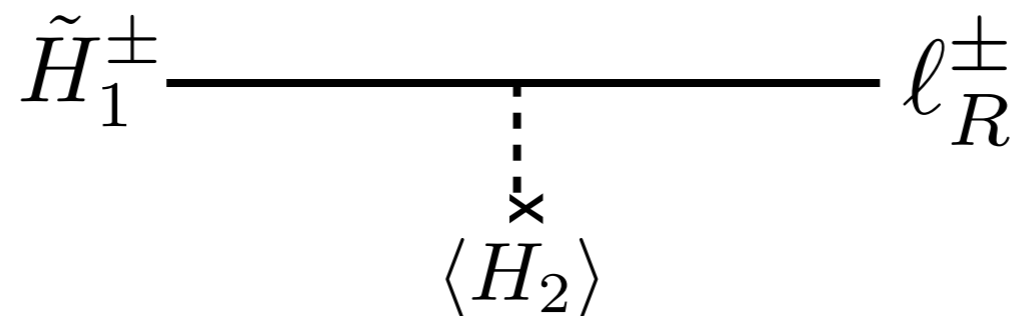
With 2 down-type higgses,  $H_d$  and  $\sigma_d$ , we can write

$$\frac{\langle \Phi \rangle}{M_{5\bar{5}}} H_d \sigma_d E^c \quad \left( \begin{array}{l} \text{absent in MSSM} \\ \text{because } H_d H_d \equiv 0 \end{array} \right)$$

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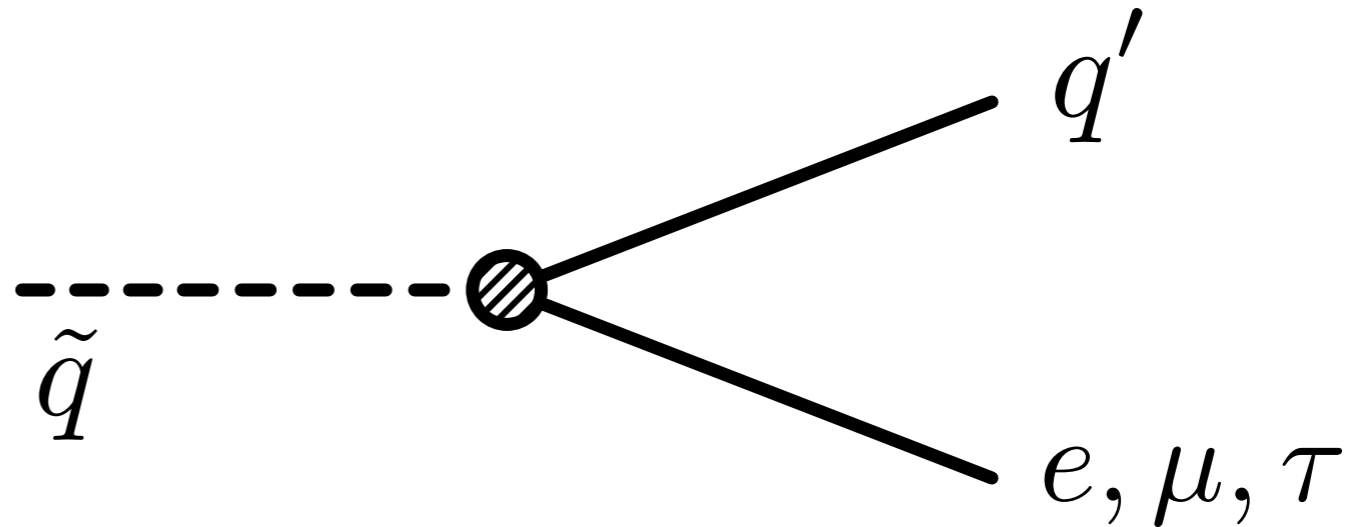
constraints are chiral suppressed

$$\mu \rightarrow e\gamma : \quad |C_\mu C_e| < 3 \times 10^{-6} \left( \frac{m_{\chi^\pm}}{100 \text{ GeV}} \right)^2$$

# New RPV operator

SUSY signatures are LSP dependent

squark LSP:  
decay like leptoquark



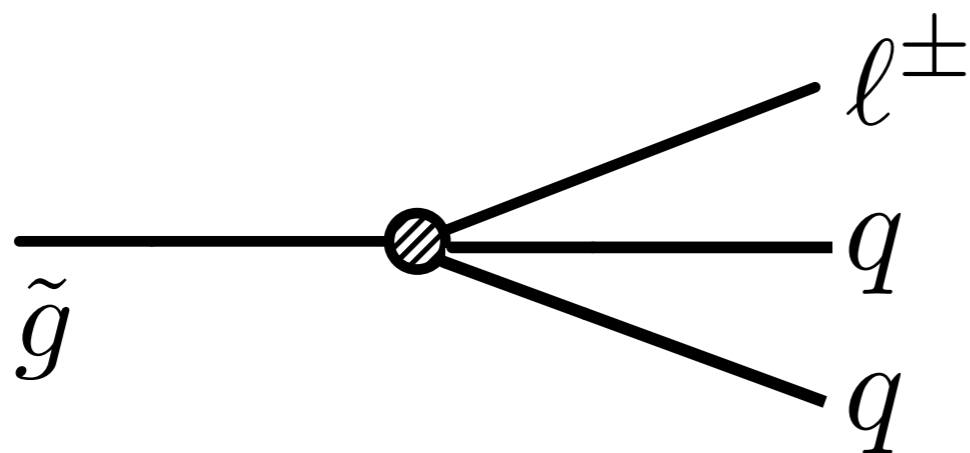
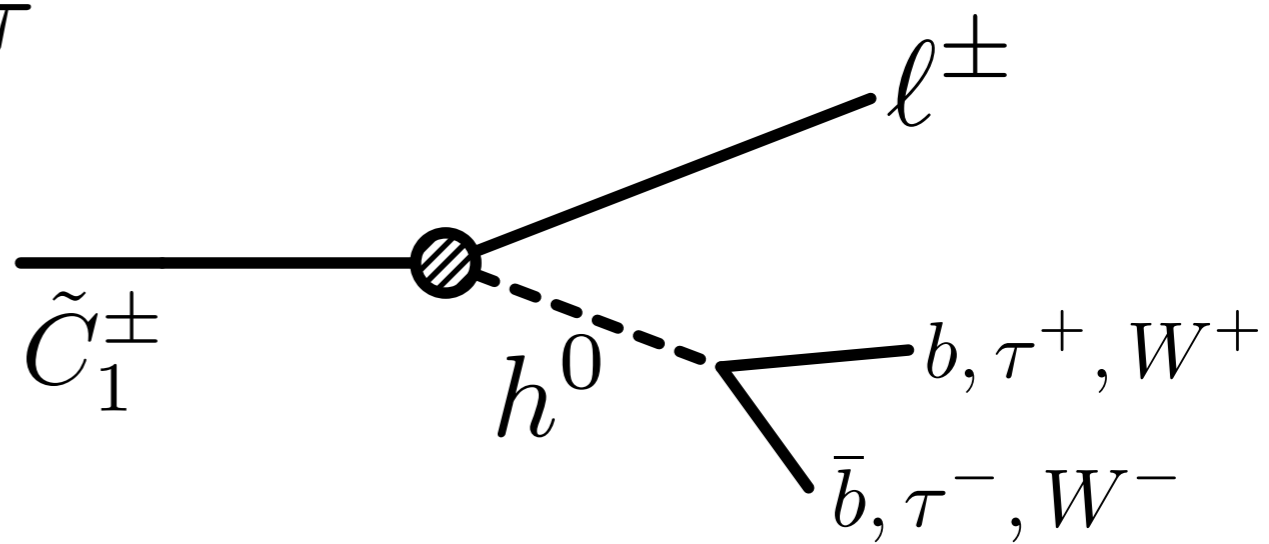
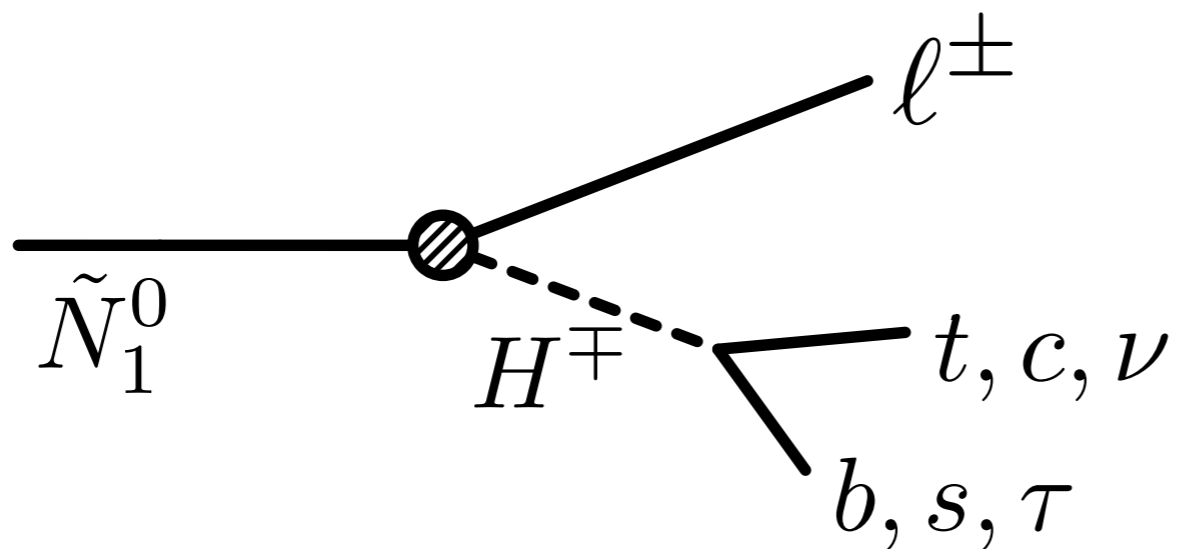
leptoquark searches:  
(1<sup>st</sup>, 2<sup>nd</sup> gen)

$$m_{\tilde{q}} > \begin{array}{l} 880 \text{ GeV } (e^{\pm}) \\ 900 \text{ GeV } (\mu^{\pm}) \\ 720 \text{ GeV } (\tau^{\pm}) \end{array}$$

dedicated CMS  
search  $\tilde{t} \rightarrow \tau b$ :

$$m_{\tilde{t}} > 525 \text{ GeV}$$

# New RPV operator

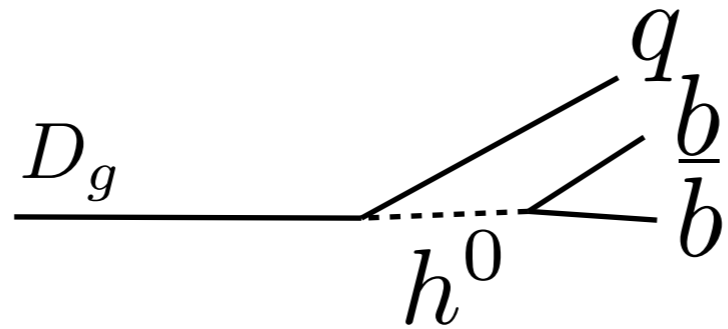


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# Sister-quarks

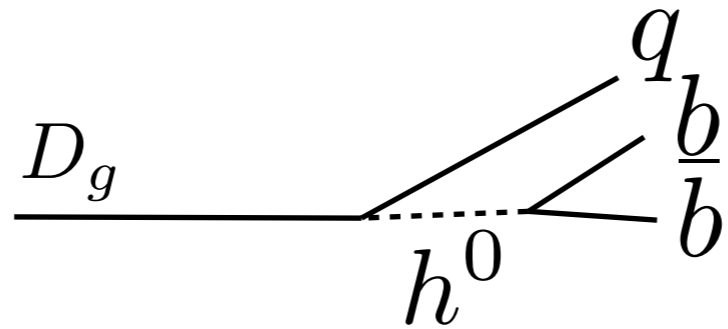
sister-quark quark mixing :  $\bar{\Phi} D_u^s D^c$



3-jet resonances  
with many b-jets

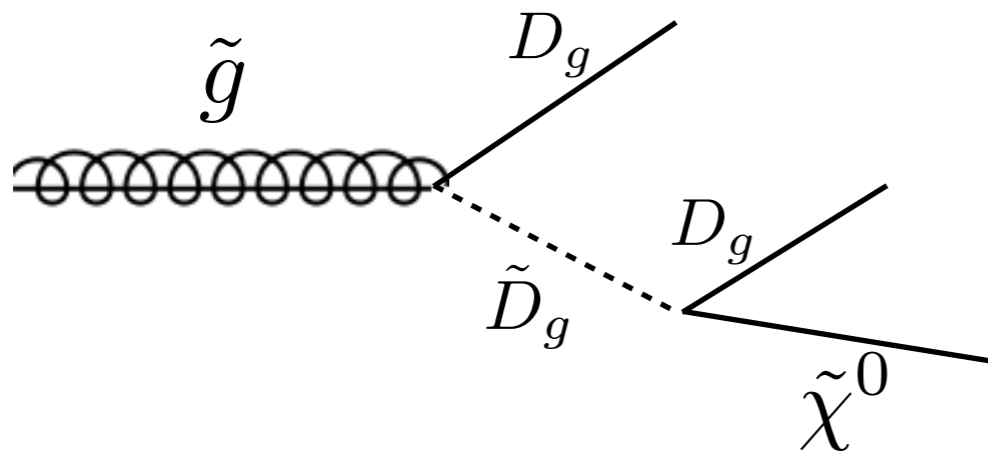
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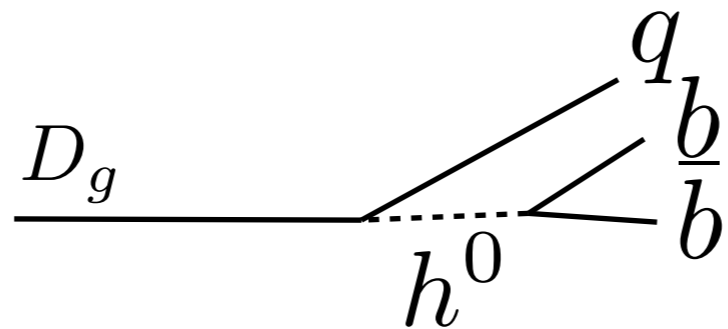
If squarks heavier than gluino,  $\tilde{g} \rightarrow D_g \tilde{D}_g$  will be dominant decay



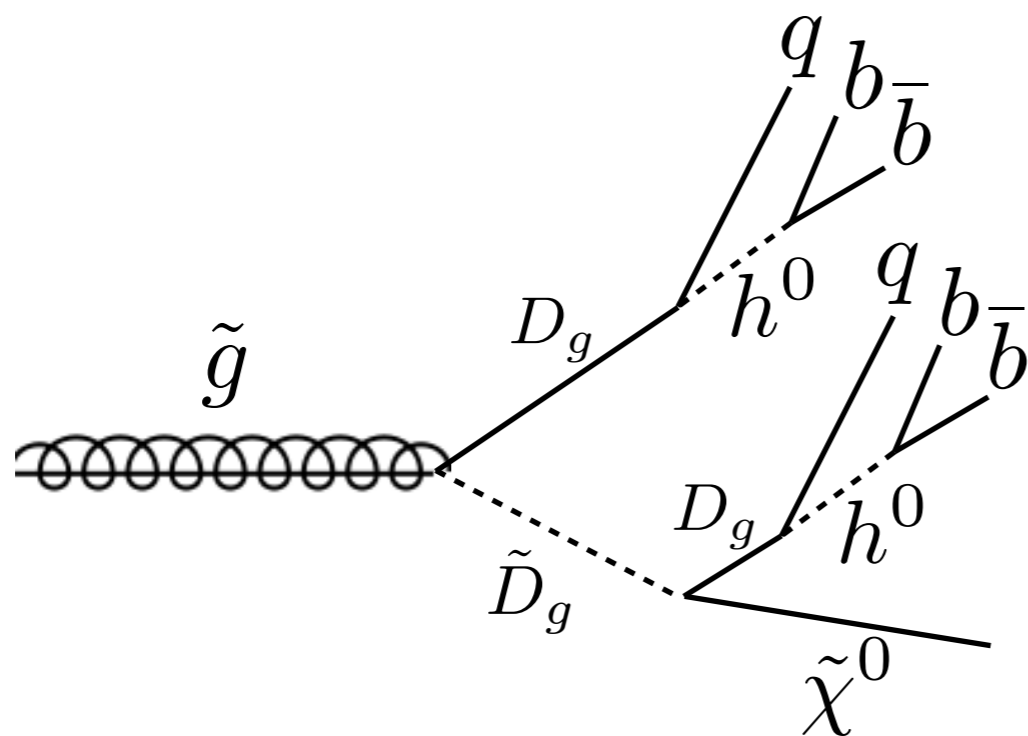


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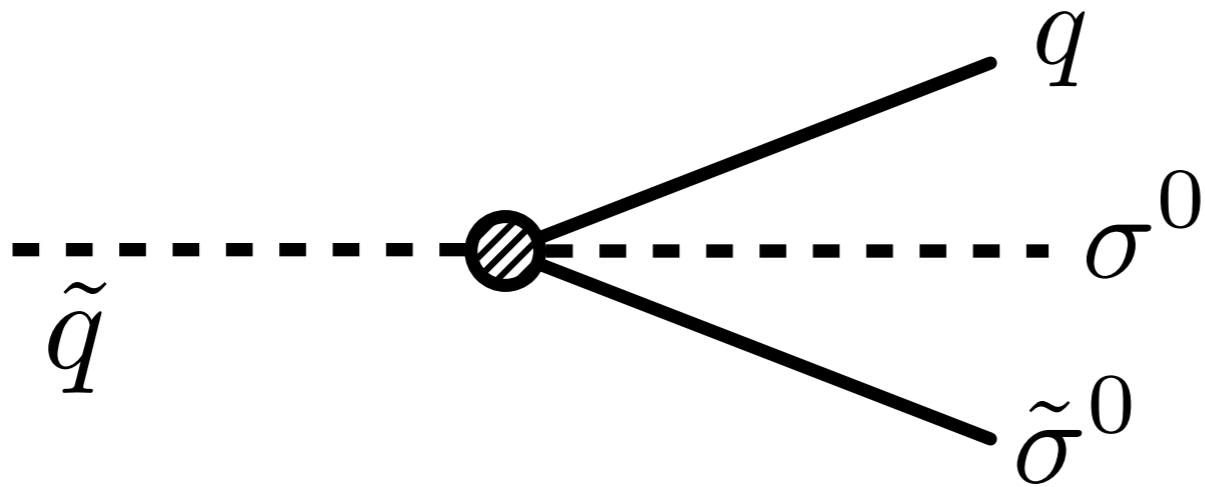


constrained by jets+MET

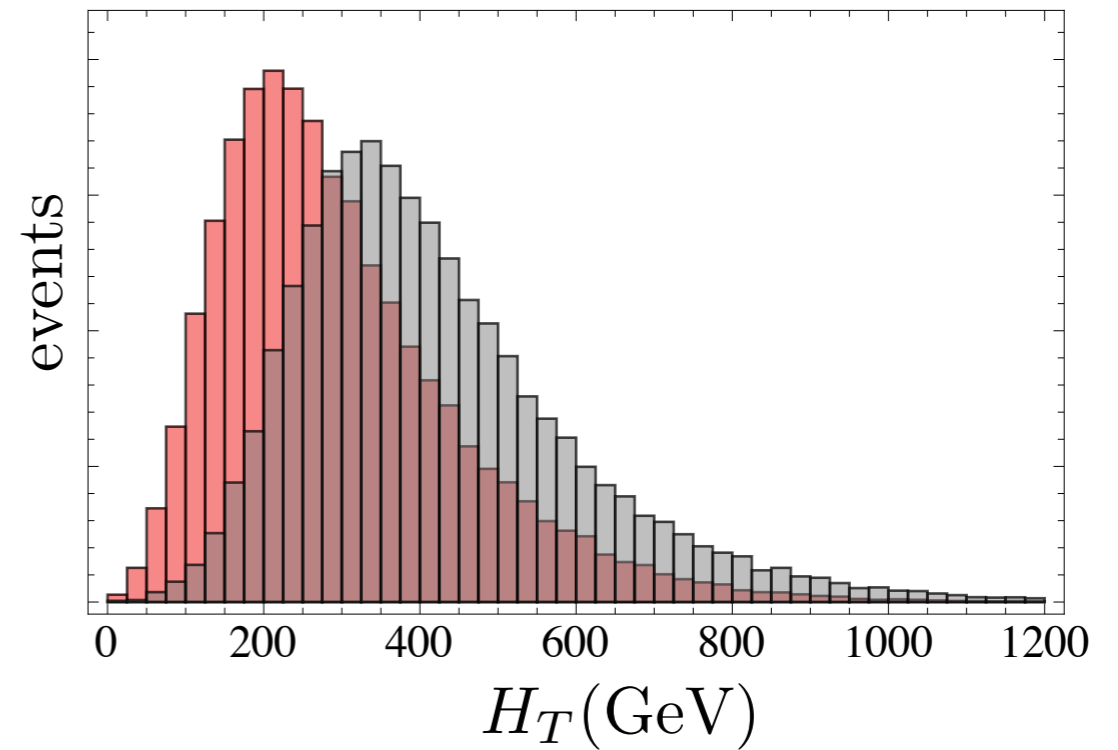
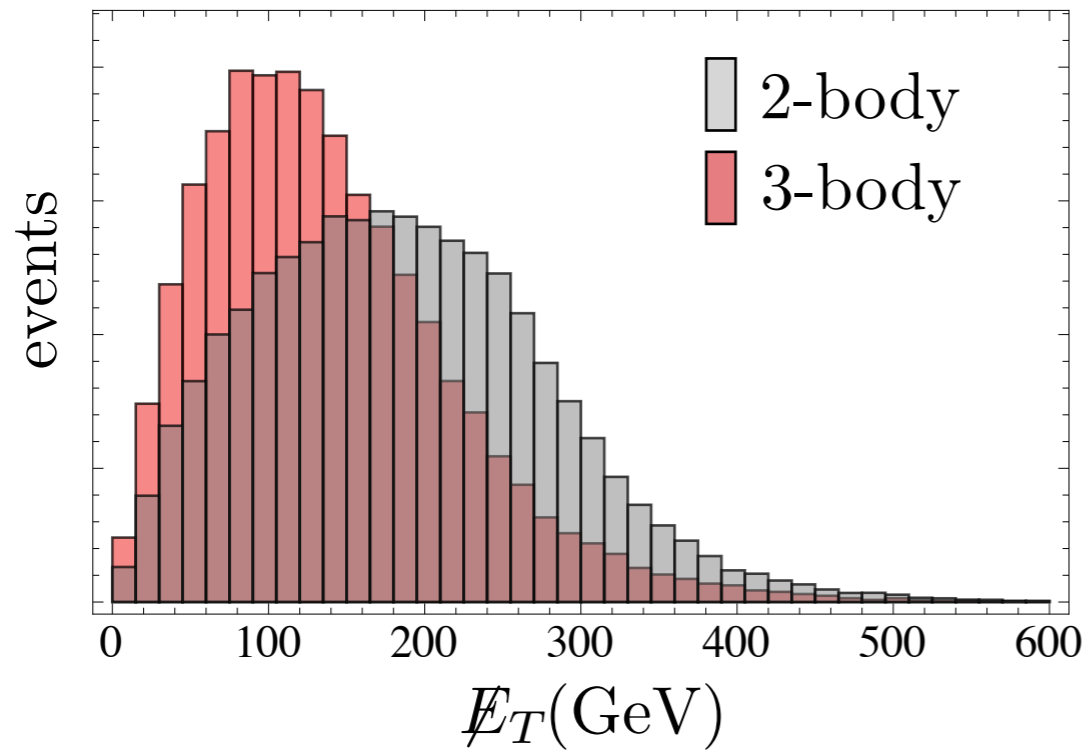
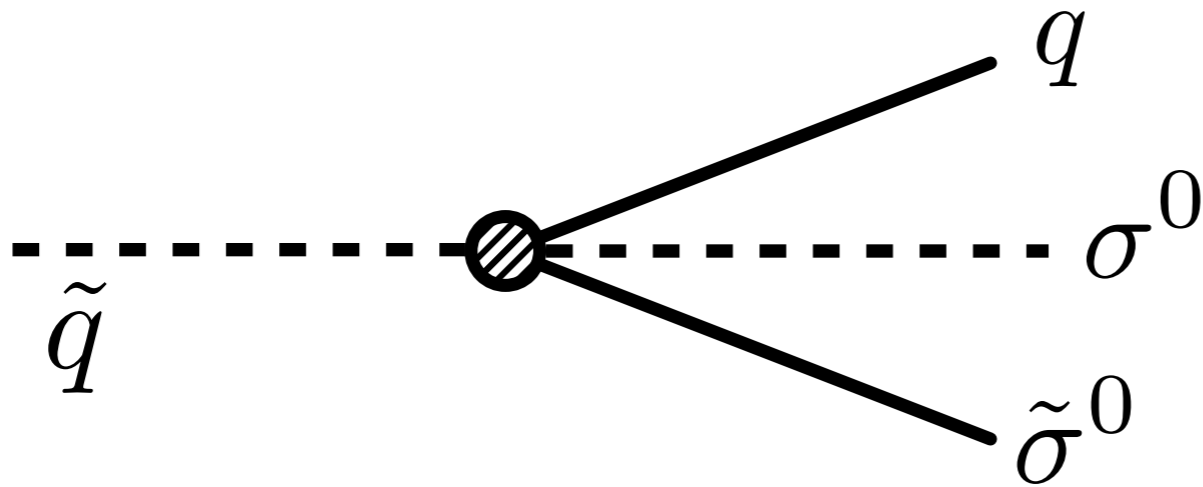
ATLAS high jet-multiplicity

$$m_{\tilde{g}} > 750 \text{ GeV}$$

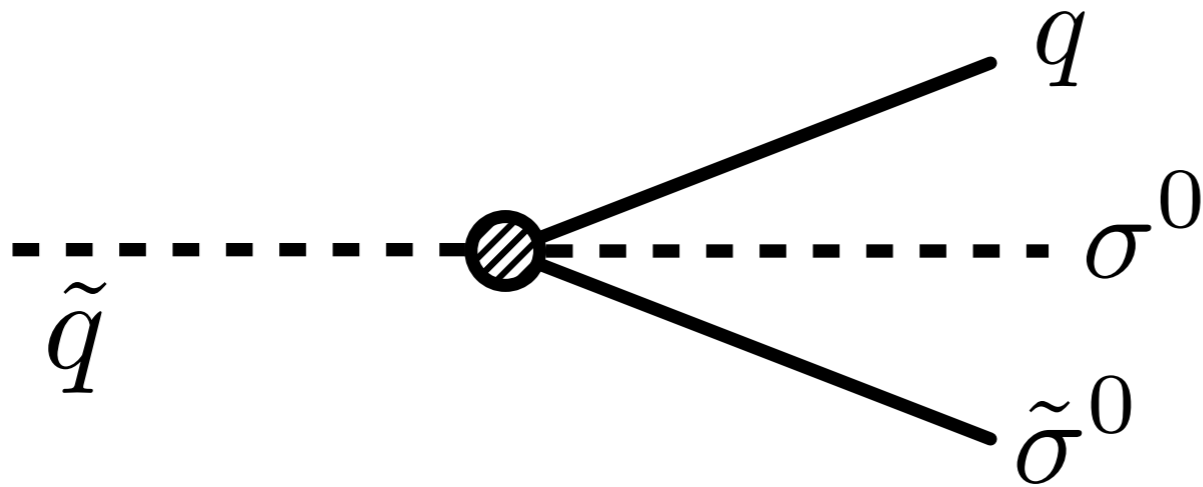
# Lightest Sister Particle as LSP



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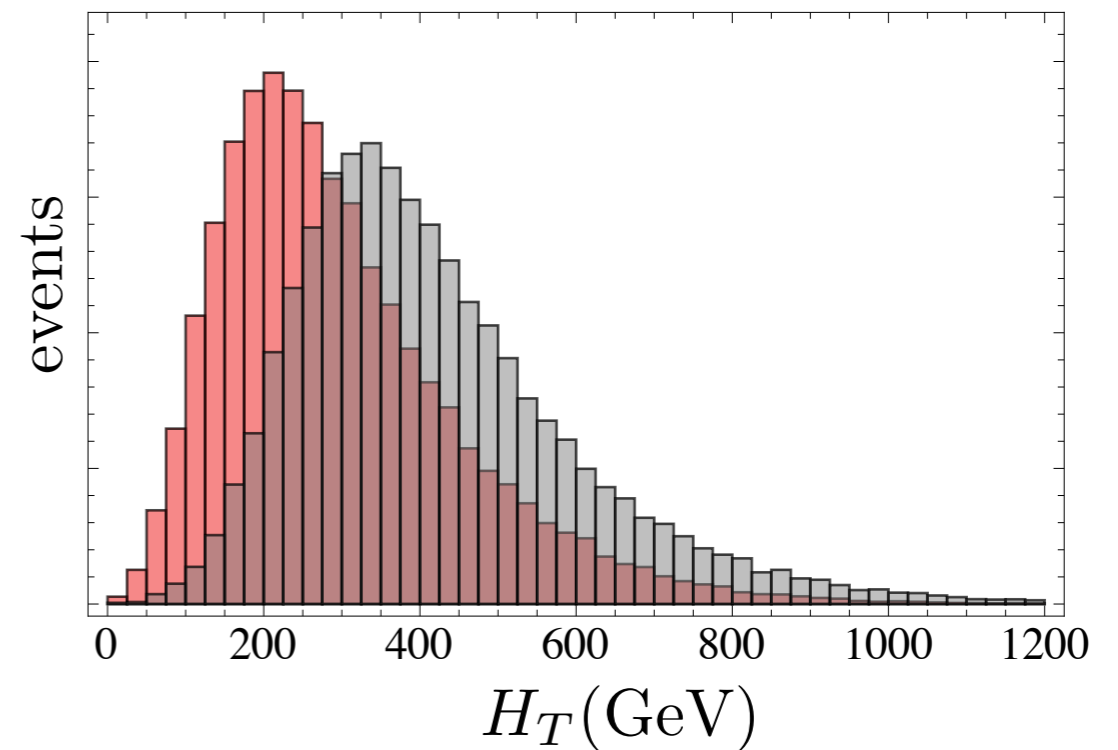
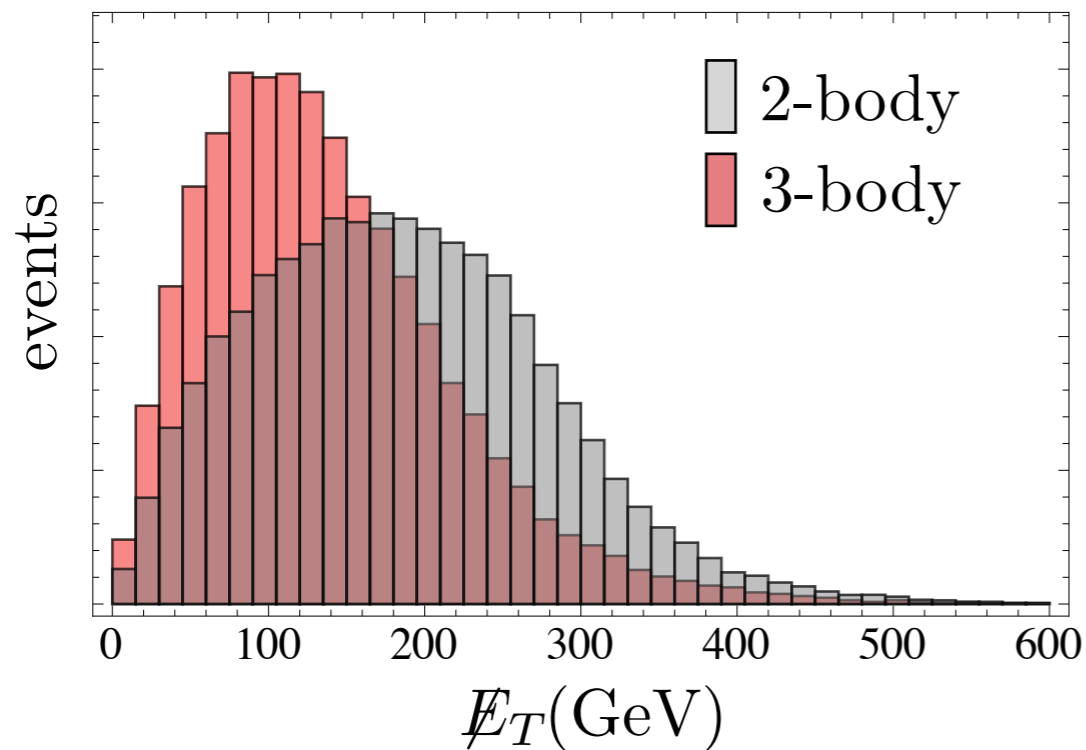
# Lightest Sister Particle as LSP



$$m_{\tilde{q}} \sim 400 \text{ GeV}$$

$$m_{\tilde{b}} \sim 300 \text{ GeV}$$

become marginally  
allowed

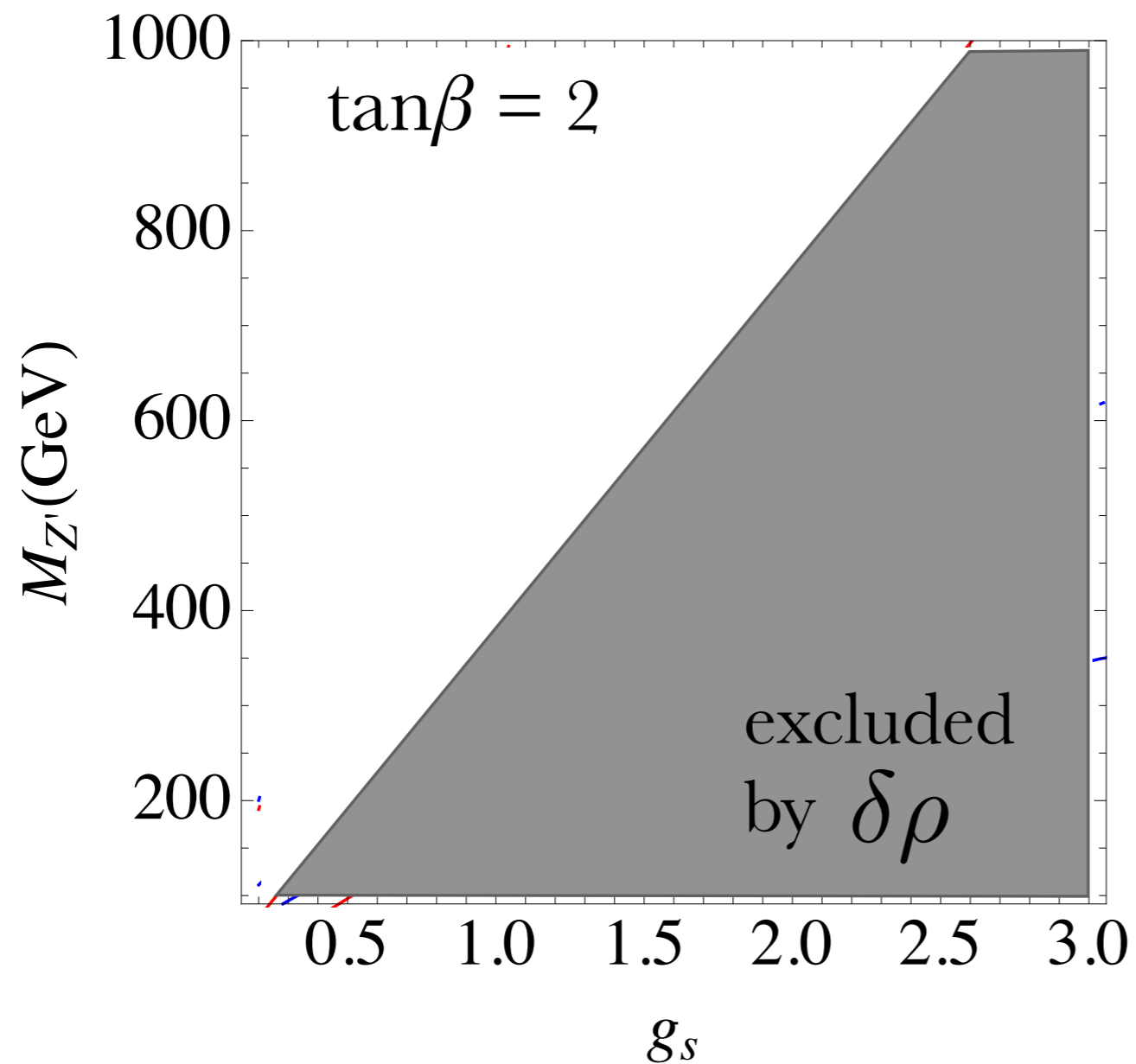


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# Light $Z'$

$\langle \Sigma_d \rangle$  mixes  $Z^0$  with  $Z_s^0$        $\theta \simeq \frac{g_s}{\sqrt{g^2 + g'^2}} \frac{m_{Z^0}^2}{m_{Z_s^0}^2} \cos^2 \beta$



$$Z' \rightarrow Z^0 h^0, W^\pm H^\mp$$

# Sister DM

Sister-charged Dirac neutralinos

$$\tilde{\Sigma}_s^0$$

$$\tilde{\phi}_s$$

$$\tilde{W}_s$$

# Sister DM

Sister-charged Dirac neutralinos

Strongest constraint: direct detection  $Z^0$  exchange

$$\tilde{\Sigma}_s^0$$
$$\tilde{\phi}_s$$
$$\tilde{W}_s$$



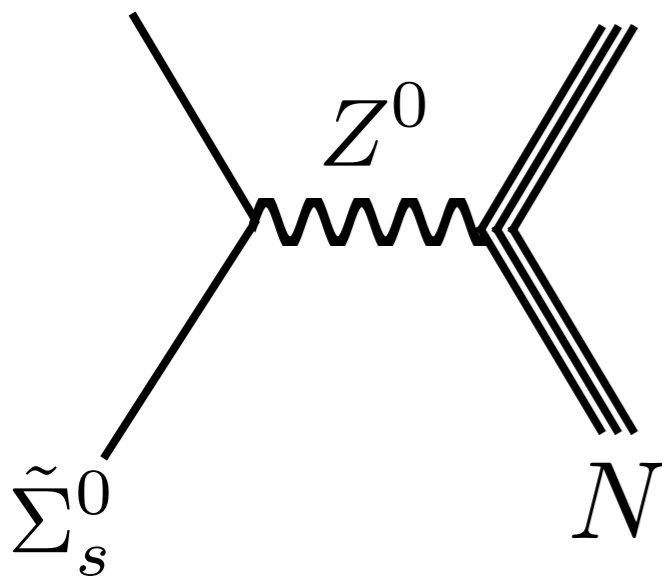
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$$\tilde{\Sigma}_s^0$$
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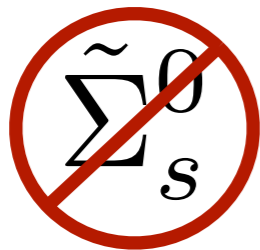
EW doublet



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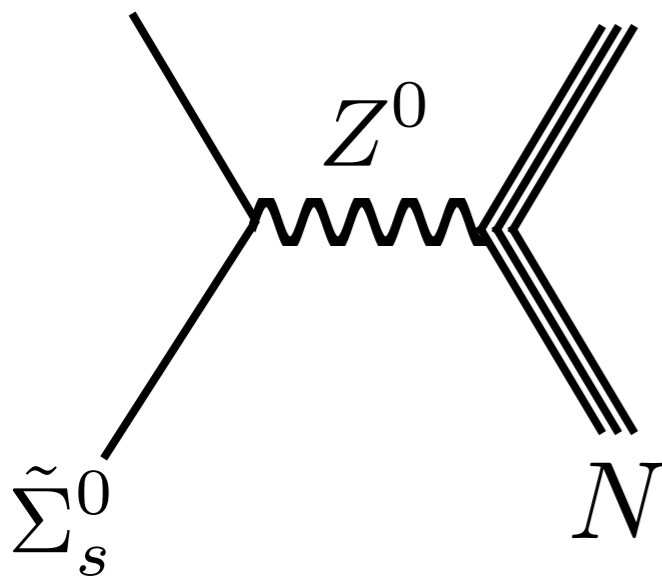
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$\tilde{\phi}_s$

$\tilde{W}_s$

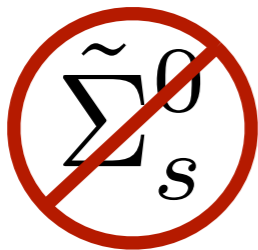
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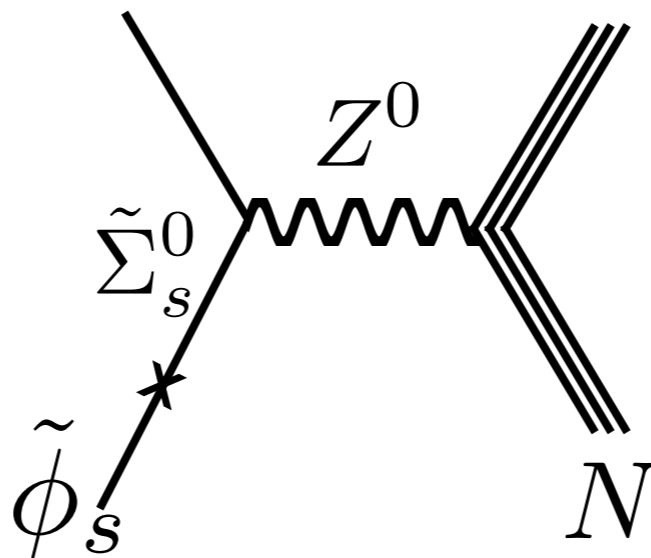
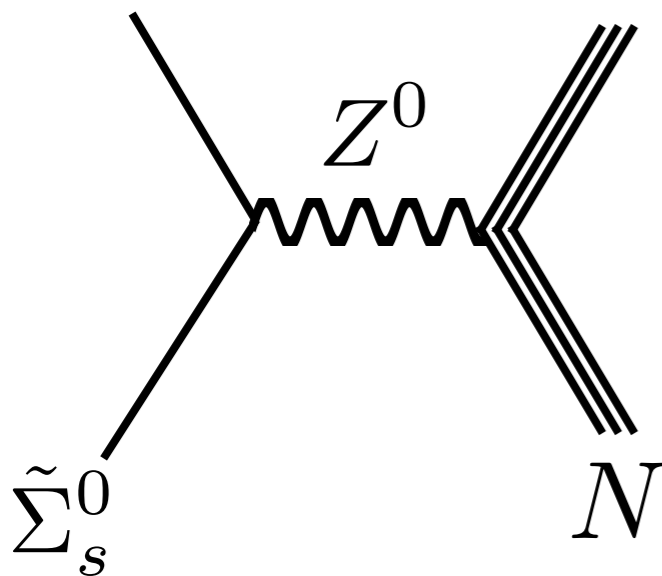


$\tilde{\phi}_s$

$\tilde{W}_s$

EW doublet

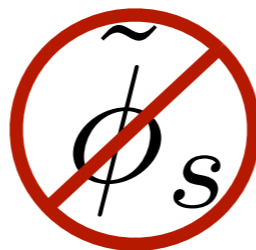
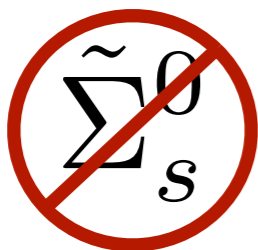
mixes with  $\tilde{\Sigma}_s^0$   
through  $\lambda_u \langle H_u \rangle \Sigma_d \Phi$



# Sister DM

Sister-charged Dirac neutralinos

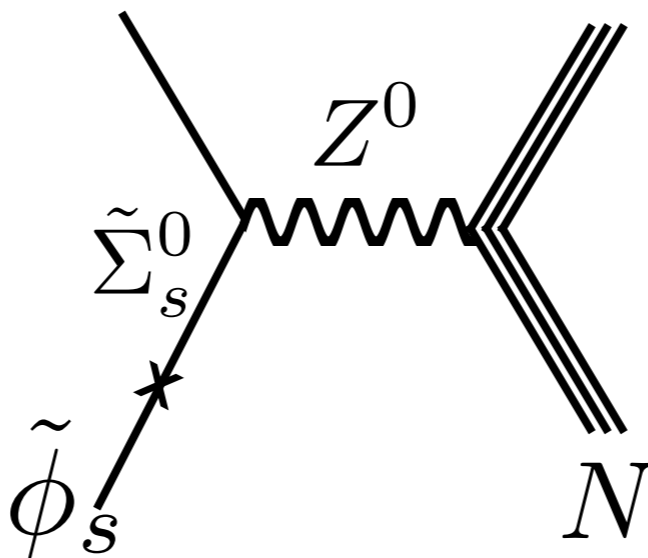
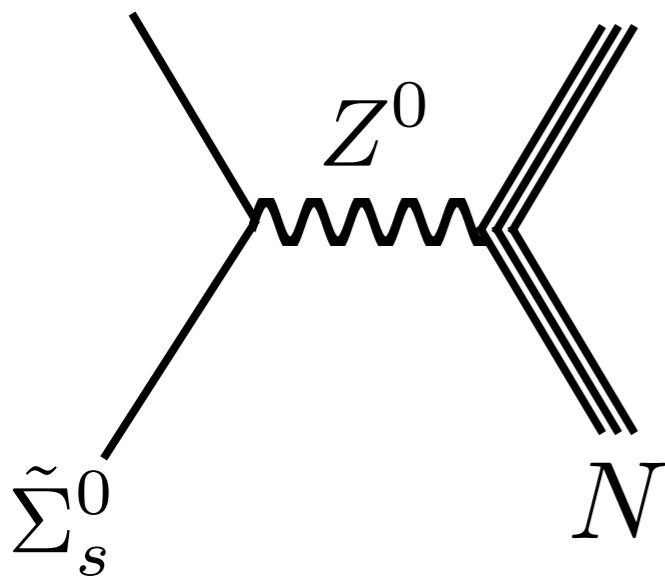
Strongest constraint: direct detection  $Z^0$  exchange



$\tilde{W}_s$

EW doublet

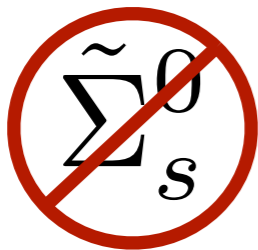
mixes with  $\tilde{\Sigma}_s^0$   
through  $\lambda_u \langle H_u \rangle \Sigma_d \Phi$



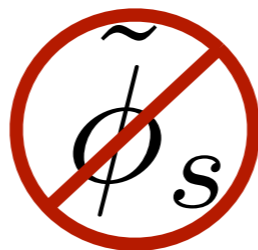
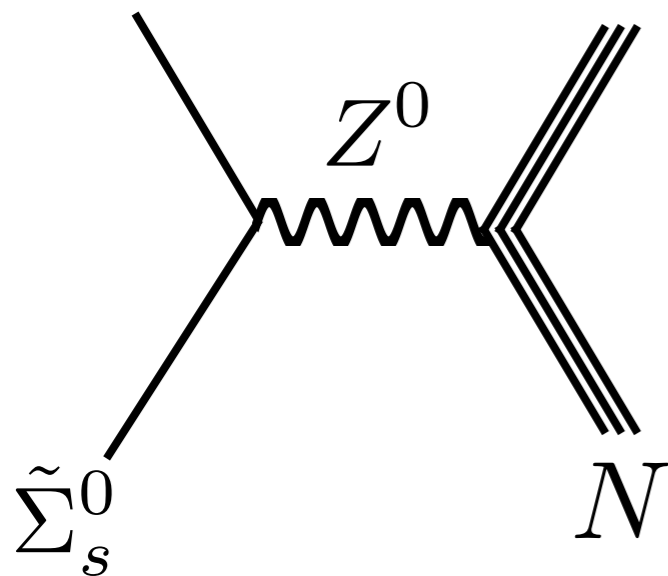
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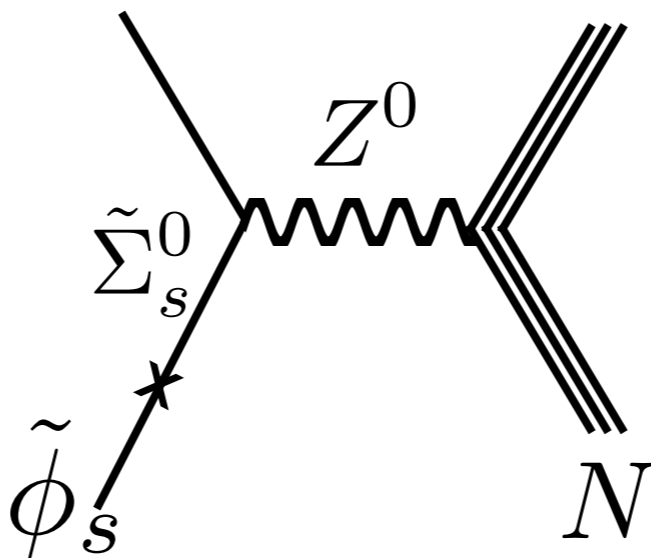
Strongest constraint: direct detection  $Z^0$  exchange



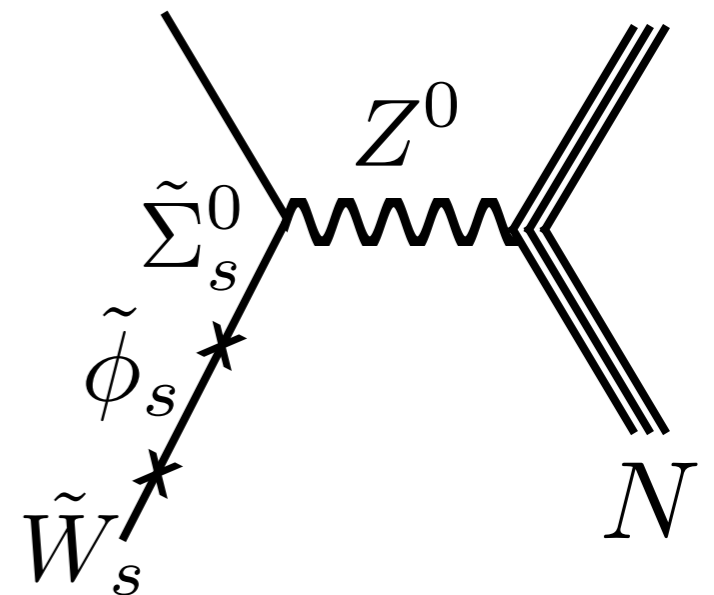
EW doublet



mixes with  $\tilde{\Sigma}_s^0$   
through  $\lambda_u \langle H_u \rangle \Sigma_d \Phi$



mixes with  $\tilde{\phi}_s$



# Sister DM

viability of  $\tilde{W}_s$  as dark matter:

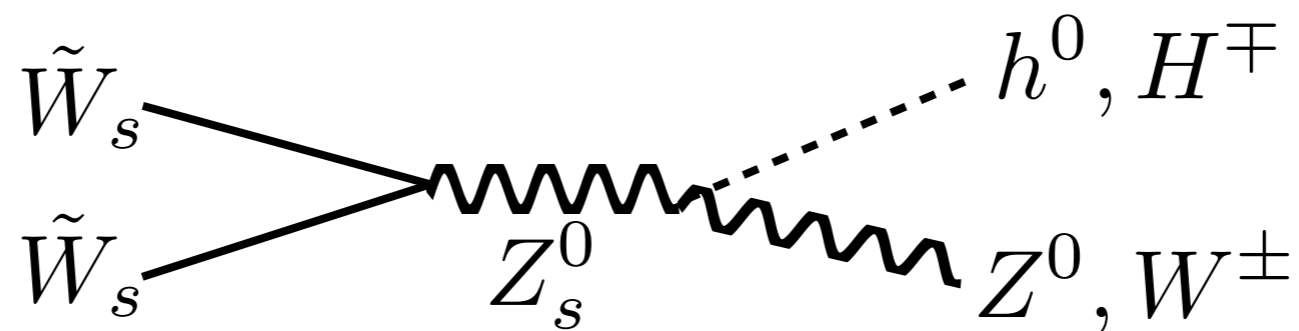
$\tilde{\Sigma}_s^0$ ,  $\tilde{\phi}_s$  need to be at  $\sim \text{TeV}$   
to suppress mixing  $\Rightarrow$  tuning of EW scale

# Sister DM

viability of  $\tilde{W}_s$  as dark matter:

$\tilde{\Sigma}_s^0$ ,  $\tilde{\phi}_s$  need to be at  $\sim$  TeV  
to suppress mixing  $\Rightarrow$  tuning of EW scale

relic abundance set by s-channel  $Z_s$  annihilation



needs to be near-resonance:

$$2 m_{\tilde{W}_s} \approx m_{Z_s} \pm 10 \text{ GeV}$$

# Sister DM

Alternatively:

$\checkmark \tilde{\Sigma}_s^0$

$\checkmark \tilde{\phi}_s$

$\checkmark \tilde{W}_s$

make it light enough to evade DD

add inelastic splittings  
(breaks  $U(1)_s$  but preserves  $Z_2$  symmetry )



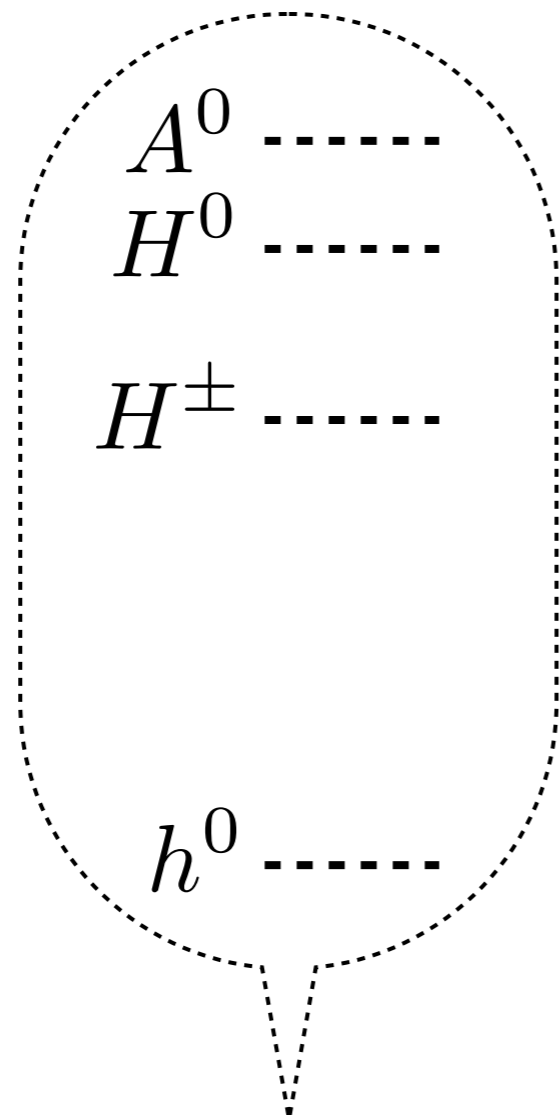
# Conclusions

- ➔  $m_h \sim 125$  GeV might be an indication of an extended Higgs sector
- ➔ Sister Higgs provides a natural and perturbative explanation
  - ➔ extra contributions to higgs quartic a la NMSSM
  - ➔ new higgs fields charged under new gauge group
  - ➔ rich phenomenology

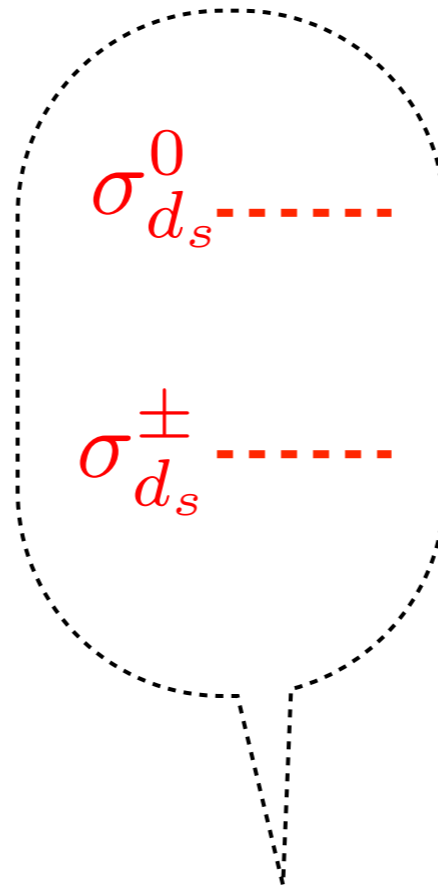
Back up slides

# Bosonic Spectrum

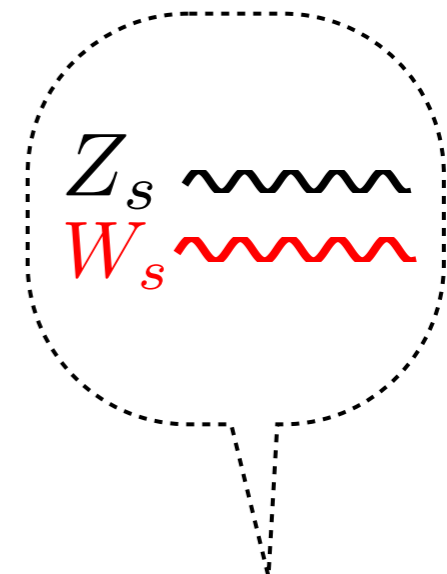
$M^2$  ↑



$H_u, \sigma_d$

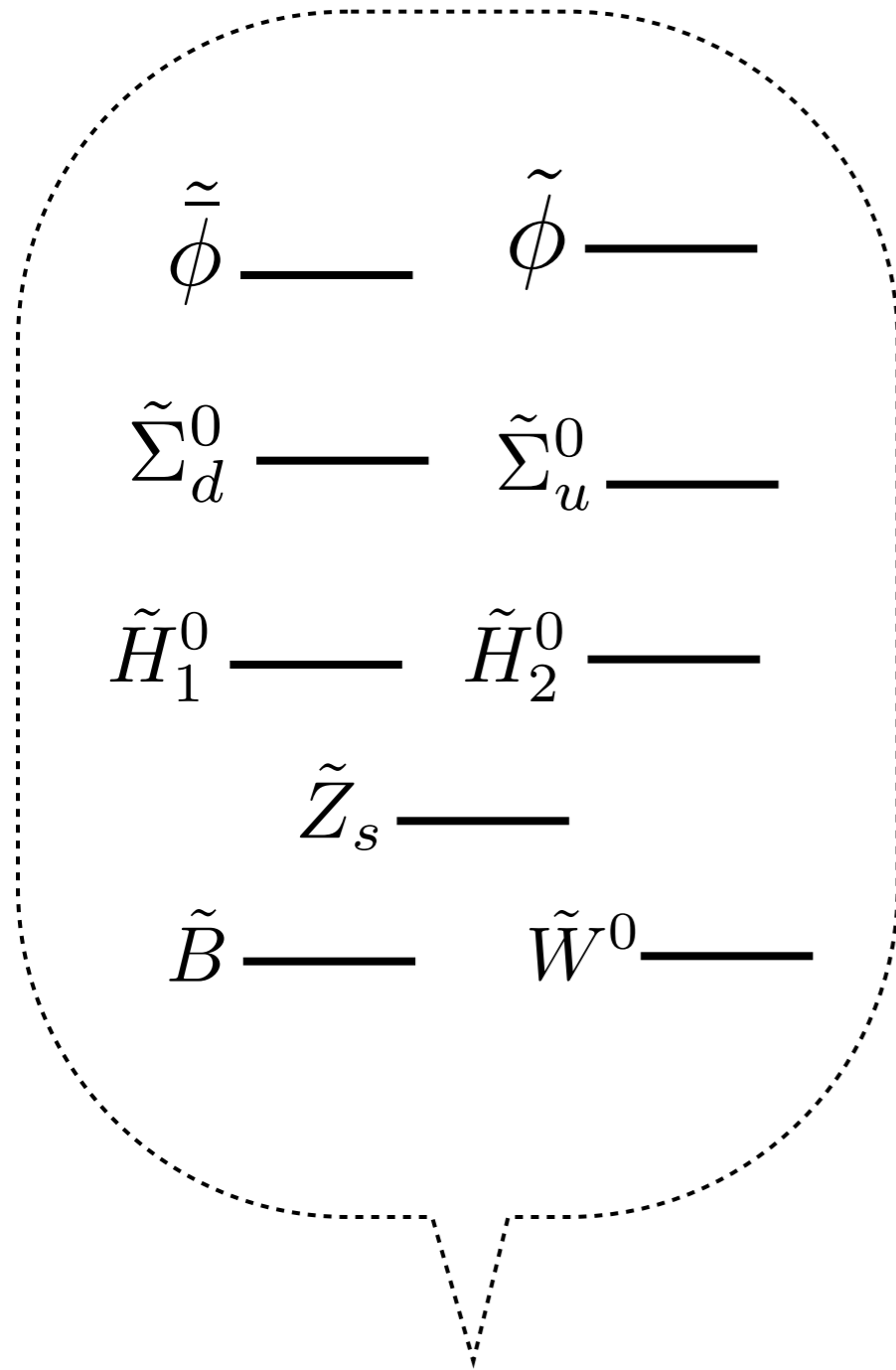


inert doublet

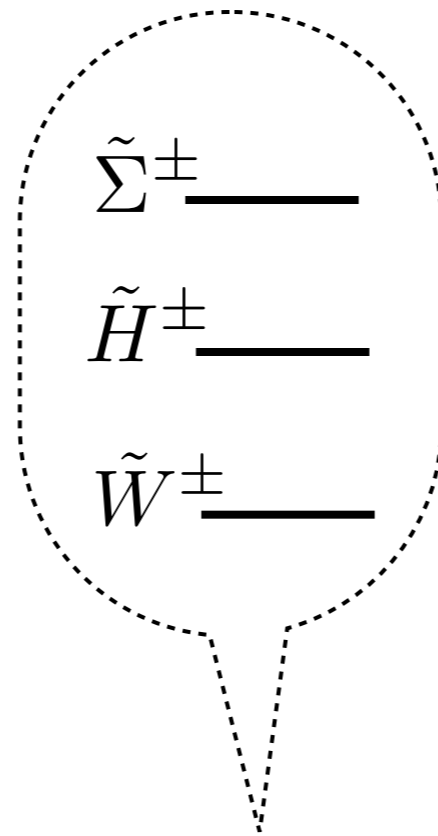


$G_s$  gauge bosons

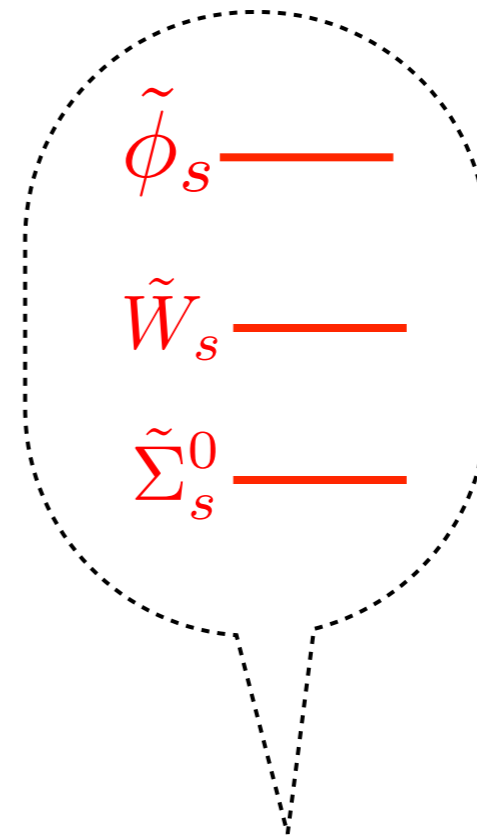
# Fermionic Spectrum



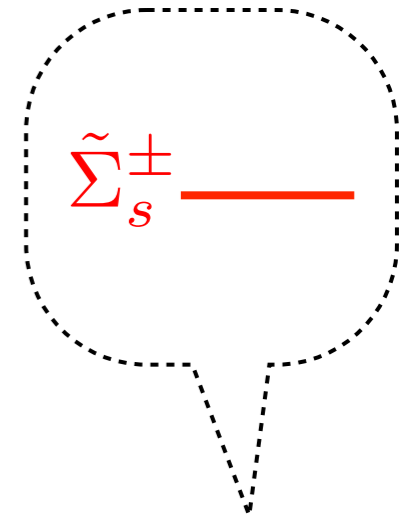
Majorana  
neutralinos



charginos



Sister-charged  
neutralinos  
(Dirac)



Sister-charged  
chargino